U.S. AIR FORCE SUPERCONDUCTING GENERATOR DEVELOPMENT

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A review of Air Force-sponsored development of a 12,000 RPM superconducting generator is presented. Results are given for recent critical component tests including stator coils and four coil rotor assembly. A brief discussion of potential future work in high power superconducting generators is given. Superconducting generators with specific weights of less than 0.1 lb/kva in the multimegawatt class can be anticipated.

Introduction

The use of superconducting wire in the rotating field winding of generators having ratings of tens of megawatts offers significant savings in size and weight over conventional generators utilizing copper wire field windings. Also, since the excitation requirements for the field winging are negligible and the iron (stator shield) losses are small, the efficiency is high. Higher terminal voltages are possible since conventional iron teeth are eliminated from the stator and hence more stator space is available for dielectric materials to withstand high voltage.(1) For these reasons, the S/C generator is an attractive candidate for applications requiring minimum weight power supplies at high power and high voltage.

These advantages are partially offset by the complicated liquid helium rotor cooling subsystem required to keep the superconducting windings near absolute zero. This critical problem and other technical challenges have been the subject of an exploratory development program sponsored by the U.S. Air Force since 1971. (2) The first phase included parametric analyses to select the lightest weight preliminary machine design. Also involved was experimental evaluation of critical components such as dynamic cryogenic seals, power leads and superconducting windings. This phase was successfully completed in January 1974 with 12,000 RPM, full field excitation tests of a superconducting rotor. (2) Detailed design of a 10 MVA superconducting generator incorporating improvements resulting from experience with the first rotor, was completed in January 1975. These results have been previously reported. (3) A cross section of the final generator design is shown (Figure 1). Fabrication of the generator is presently underway; testing will be performed in 1977.

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A summary of major machine characteristics is given below:

Power rating (Field Current (amps)/Power MVA): 197/1.0, 223/5.0, 246/10.0

Voltage: 5KV Line-to-Line, Efficiency: 98.36%, Frame Diameter (max): 19 inches, Bearing to Bearing Length: 29.8 inches, Volume: 4.9 ft^3, Total Generator Weight: 939 lbs (.09 lbs/KVA @ 10 MVA), Rotational Speed: 12,000 RPM, Frequency: 400 Hz, Superconductor (field): Niobium Titanium, Number of poles: 4, Stator Connection: 3 phase, wye, two parallel circuits.

This paper presents progress during generator fabrication, results of some critical component tests on the stator and four coil rotor assembly, discussion of proposed generator testing, and a brief review of potential future work.

GENERATOR FABRICATION

Difficulty was encountered in forming the twelve (normally conducting copper) stator coils which rest upon the fiberglass-epoxy bore seal (Figure 2). The end turn extensions had to conform to the surface curvature of the bore seal and lay flush against the bore seal. The finely stranded copper wires (o.044" x 0.0595" strand cross section) used to reduce eddy current losses were not stiff enough to keep all strands in place during coil forming. Relaxed geometry requirements allowed end turn extensions to ride up above the bore seal; the "knuckles" on the end turns were then higher than originally anticipated, requiring the stator backiron (or shield) to be cut in half and welded together.

A problem was encountered in achieving a suitable mechanical fit between the support structure and the four superconducting field coils. The support structure consists of a stainless steel machined counterform of the stepped racetrack coil structure (Figure 3, only the side, or quadrature, covers are shown). Since the coil dimensions after winding did not fit the counterform exactly, shimming was required to fill the spaces between the coils and the covers. The coils must be totally supported to prevent movement under large magnetic forces. Wire movement can cause the superconductor to revert to the normally (resistive) conducting state.(4) The bolts (Figure 3) are used to tighten the covers to compress the windings before closure welds are made.

The severe shorting problem in the field windings encountered in the Phase I rotor has been solved through the use of an improved insulation system. These shorts limited the charging rate of the field coil, due to I^2R losses, to 246 amperes in 14 minutes. The present insulation system consists of an insulating layer on the wire with a polysulfone overcoat which softens upon heating and allows a rigid bonded coil structure. An insulating layer was also applied to the inside of the coil support structure. With this insulation system, the four coil assembly was excited to 243 amperes in 40 seconds under nonrotating conditions. This corresponds to a magnetic field ramp of about 1.0 Kgauss/sec; tests indicated that no shorting occurred in the coils.

SUBSYSTEM TESTS

To determine actual volt-ampere power rating, oil flow cooling tests were performed on a statorette (stator winding mockup) and static superconducting tests were performed on the four coil assembly. The stator cooling utilizes oil flow through the interstices of the stranded conductor, each conductor consisting of 18 strands (Figure 4). There are three conductors per coil and two coil sides on top of each other in a "slot", since a conventional double layer, reentrant, winding scheme is used. A statorette was used to simulate the oil flow conditions through a single "slot". Conductor U-channels, wedges and spacers made of dielectric material form the slot, rather than iron teeth as in conventional iron core generators. Oil enters the stranded conductors at the center of the active length ("channel region") and flows through the interstices out into the end turn region where the strands are in loose array and oil can exit from the conductor. The end turn region is flooded with oil. Joule heating is determined by conductor current density (16,210 amps/in^2). Eddy current loss varies with the square of the frequency, magnetic field strength and strand diameter, and inversely as the resistivity of the material, and occurs primarily in the active length of the conductors. Stator losses are: I^2R: 109 KW, Eddy Current: 46KW, Iron Shield: 8KW. If the temperature of the entire length of the conductor is assumed constant, almost 60% of the joule heating occurs in the end turns.

Initial oil flow tests showed only 10% of the design value of 50 psi. For an applied 400 Hz current of 600 amperes, steady state conductor temperature was 205°F in the active region and 366°F in the end turns. It was shown that reduction was caused by adhesive blocking the inlet. A second statorette (constructed with a different adhesive) demonstrated the required flow rate of 50 gpm at 25 psi (Figure 5) Calculated hot spot conductor temperatures at 50 gpm and oil inlet temperature of 150°F are 255°F in the active region and 275°F in the end turns assuming equal flow distribution. Unfortunately, unqual (3/1) oil distribution was observed. Use of lower viscosity transformer oil should allow a flow rate as high as 80 gpm total, which would produce a maximum operating temperature of 239°F in the active region for this unbalanced flow. Since the stator operating limit is 300°F, reserve cooling capacity should enable the generator to operate at 10 MVA for a few hours.

Current carrying capability of the field windings was determined by immersing the four series - connected coils in liquid helium in a large dwar, and charging them at various excitation rates to normalization. Two series of coil tests were performed. Rated current for 10 MVA (246 amps) was attained only twice. Some evidence of training (increase of normalization current with successive current applications) is apparent. The inside of the support structure was machined to apply additional compressive force on the windings. No improvement resulted, implying insufficient precompression. If normalization were due to material defects, the test at coil temperatures of 3.3°K (Figure 6) should have raised the critical current level and resulted in a higher current at quench. That this did not occur supports the hypothesis

that rapid conductor movement at a threshold force level caused the quenches.

GENERATOR TESTING

Load testing will involve steady state and sudden loads. The former will provide information about thermal capabilities of the stator, eddy current losses, and lifetime expectations. The latter will determine if the field winding can maintain its superconducting state under rapid winding magnetic field changes and will determine the effects of transient torques and crushing loads on the damper shield and the effects of severe transient electromagnetic forces on the stator structure.

Because of the high speeds, high power, high frequency, and relatively high voltage, a limited number of suitable test sites are available for full power testing. A final decision on the testing site has not as yet been made. No-load (zero power) testing will be performed by Westinghouse at the Central Research Laboratory. These tests involve open circuit and short circuit measurements and determination of some machine parameters.

FUTURE WORK

Specific weights (lbs/KVA) of a S/C generator in the 10 to 50 Mw power range are plotted (Figure 7).[1] Conservative magnetic field strenghts, ($\sim$4 Tesla), rotor tip speeds (420 ft/sec), and stator current densities ($\sim$16,000 amp. in), are assumed. New technology developments include a double damper shield system required[5] for generator operation into a rectifier and a toroidal stator winding geometry for high voltages.[6]

A 20% increase in rotor tip speed from the present 420 ft/sec would result in a weight reduction of about 17%.[1] A 10% increase in magnetic field strength produces a 5% weight savings and permits the active length of the generator to be reduced by 10%. This results in improved rotor dynamics through raised critical speeds, and makes a toroidally wound high voltage stator more efficient.

High voltage capability of the generator does not rely exclusively on a toroidal winding geometry;[7] however, stator fabrication should be simpler, the insulation requirements are more modest, and there are no crossovers in the end turn region. In addition, (Figure 8), the specific weight of S/C generators employing toroidal windings increases more slowly with increasing output voltage as compared to high voltage, iron core, wire wound generators. The generator active length must be less than an end turn length at one end of a reentrant coil for this winding to be as efficient as a conventional reentrant winding.

Operation at high magnetic field strengths reduces the critical current density in the field winding and the allowable temperature rise. The superconductor Nb_3Sn offers significantly larger magnetic fields with improved temperature margins; this is desirable because of transient heating effects during sudden load application or removal of

operation into a rectifier, and because of possible rapid excitation requirements.

Conductor mechanical support is also crucial. The field winding wire has a critical current of about 850 amps at 40 Kgauss and 4.2K. One reason for the low critical currents actually attained ($\sim$250 amps) may be conductor movement. A possible fix is to fully impregnate the coil with an epoxy compound so that each wire is firmly fixed despite large JXB forces. One cannot then rely upon the large specific heat of the liquid helium in the winding to limit the temperature rise. Unless the temperature margin of the superconductor is sufficient, internal cooling must be provided to handle the heat generated under transient conditions.

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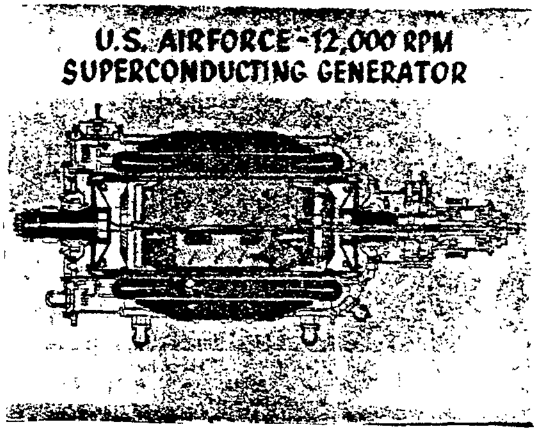
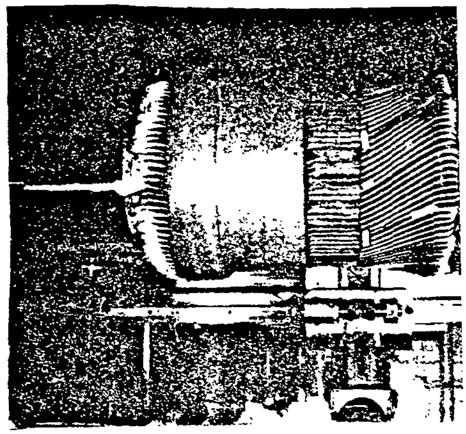


FIGURE 1



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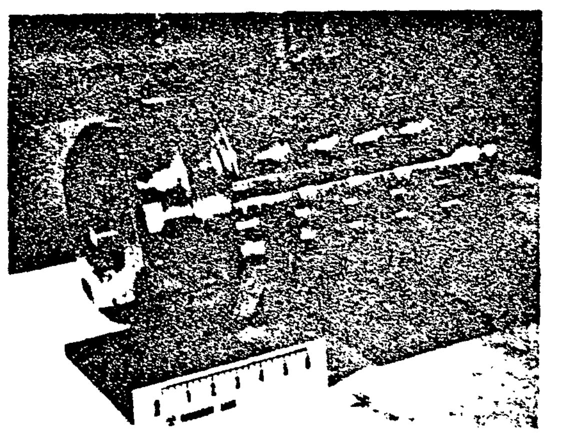

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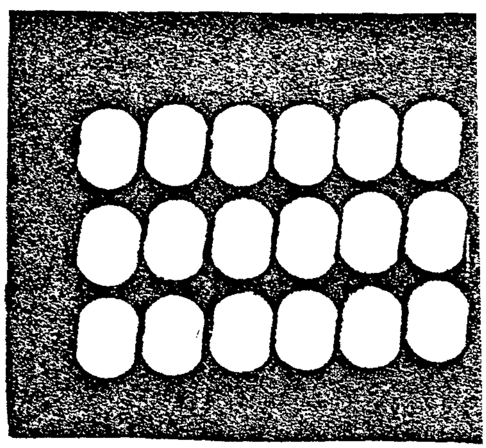

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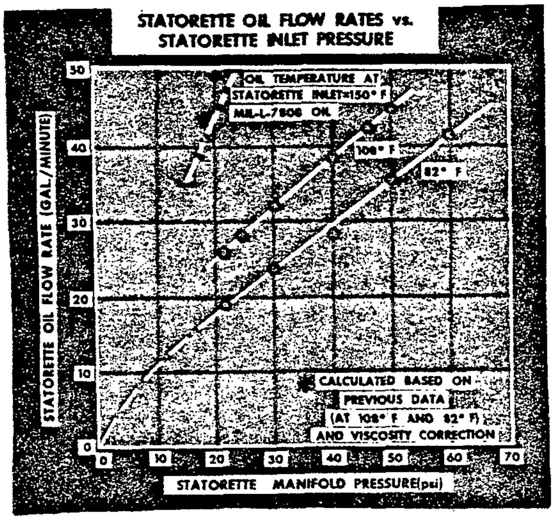

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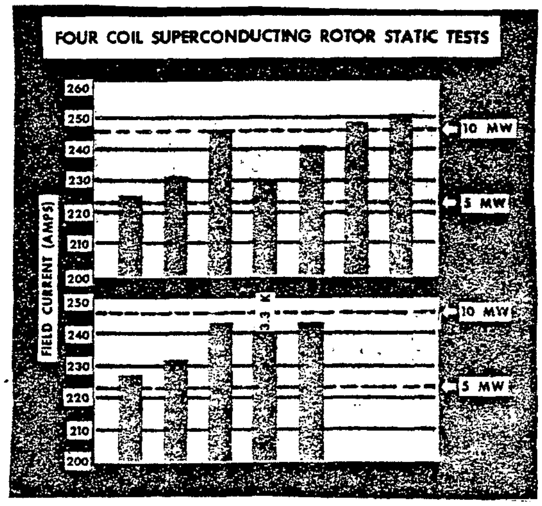

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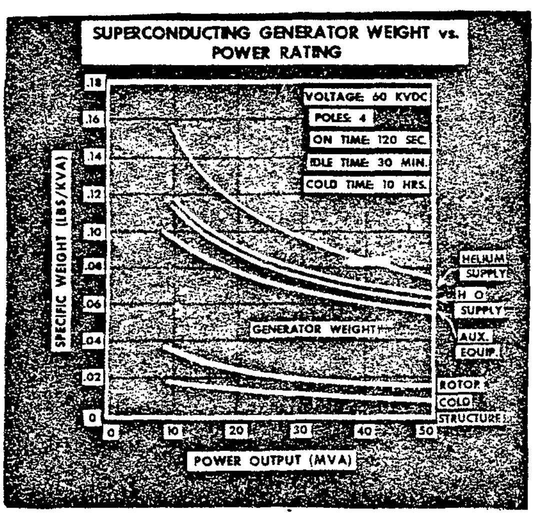

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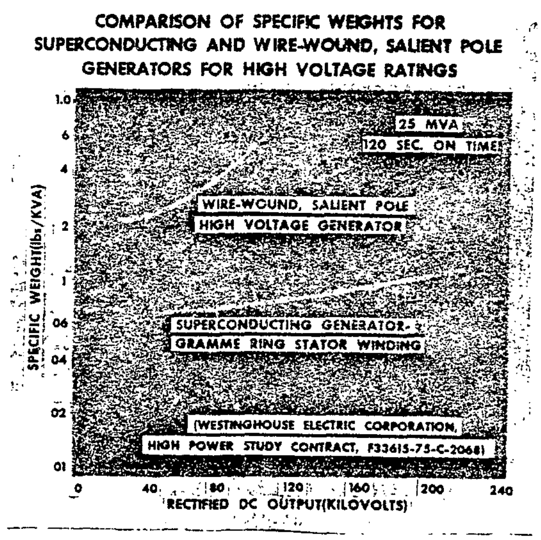

FIGURE 8